

Observations of Internal Lee Wave Generation

Eric Kunze

Applied Physics Laboratory, University of Washington

1013 NE 40th

Seattle, WA 98105-66989

Phone: 206-543-8467 Fax: 206-543-6785 e-mail: kunze@ocean.washington.edu

Award #: N000149410038

<http://www.ocean.washington.edu/people/faculty/kunze/kunze.html>

LONG TERM GOALS

My interests are in oceanic phenomena that contribute to stirring and mixing with the ultimate goal of parameterizing their impact on larger scales through dynamical understanding. Phenomena of interest range from the meso- (10 km) to the microscale (1 cm) with an emphasis on their interactions, and include internal waves, tides, potential-vorticity-carrying finestructure (vortical mode), turbulence and double diffusion.

OBJECTIVES

My recent focus has been on understanding how meso- and finescale flow fields interact with complicated topography such as seamounts, canyons, ridges and the continental slope. Mixing in the stratified ocean interior is too weak to close the meridional thermohaline circulation (Ledwell et al. 1998). I am exploring whether topographically-enhanced turbulent mixing is sufficiently large to do so, and the mechanisms responsible for its generation.

APPROACH

During May 1998, I participated in a cruise off the Virginia coast in collaboration with Drs. Kurt Polzin, John Toole and Ray Schmitt (WHOI). This observational program (TWIST – Turbulence and Waves over Irregularly Sloping Topography) was designed to characterize the internal wave and turbulence climates above a corrugated continental slope with 2-3 km wavelength ridges and gullies crossing the slope. The corrugations, in combination with low-frequency alongslope flows associated with topographic Rossby waves, were thought suitable for internal lee wave generation. I conducted surveys with expendable current profilers (XCPs) and expendable CTDs (XCTDs) to obtain 3-D snapshots of velocity (u , v), temperature T , salinity S and vertical displacement ξ over the full water depth. These measurements complement the temporal sampling of the mooring array (Toole) and the fine/microstructure profiling (Polzin) by providing spatial snapshots along and across a ridge-gully pair, as well as by providing measurements into the bottom.

WORK COMPLETED

The cruise was successful. High-quality expendable data were collected along three transects – one along the slope crossing a ridge-gully pair, one crossing the slope along a ridge and the last crossing the slope along a gully. At each of 25 stations, four XCP/XCTD pairs were deployed over a 12-h

period to allow isolation of semidiurnal from higher- and lower-frequency signals. XCP velocity profiles were made absolute by correcting them with GPS-referenced shipboard ADCP profiles. Vertical displacements $\xi(z)$ and horizontal energy-fluxes $\langle \mathbf{v}'p' \rangle$ have been estimated for fluctuations relative to station-averages, and the dominant signals identified.

The energy-flux estimation technique is new. It relies on obtaining internal-wave-induced reduced pressure perturbations ($p' = P/\rho_o$) from the hydrostatic balance $p_z(z) = b(z) = -N^2(z)\xi(z)$ and the vertical displacement profiles $\xi(z)$. Integrating the hydrostatic balance then provides the internal-

wave-induced reduced pressure $p'(z) = -\int_z^0 N^2(z')\mathbf{x}(z')dz' + \frac{1}{H} \int_{-H}^0 \int_z^0 N^2(z')\mathbf{x}(z')dz'dz$ where the

depth-average integral is removed to satisfy the ‘boundary condition’ that the depth-average internal-wave-induced pressure perturbation vanishes; this takes into account the effect of the internal-wave-induced sea surface elevation. Energy-fluxes are then obtained by multiplying the estimated pressure anomalies by the baroclinic velocity profiles and averaging over wave phase $\langle \mathbf{v}'p' \rangle$. Previous investigators do not appear to have recognized the need to remove the depth-average. This does not effect the depth-integrated baroclinic energy-fluxes, but impacts their distribution in the vertical.

During this past year, I have also shepherded to publication the last paper from the Ph.D. thesis of Joanna Muench (Muench and Kunze 2000) on internal wave interaction and acceleration of the equatorial deep jets, written a review of salt-fingering theory for SCOR Working Group 128 on Double Diffusion (Kunze 2000), and written an article on potential-vorticity-carrying finestructure (vortical mode) for the *Encyclopedia of Ocean Sciences* (Kunze 2000).

RESULTS

Signals over the Virginia continental slope are dominated by

- an alongslope subinertial jet which reversed from north- to southward just prior to the XCP/XCTD surveys. This flow is in excess of 10 cm s^{-1} in the upper water column but is weak in a bottom boundary layer a few hundred meters thick. The mean flow is sufficiently weak, even in the water column, that internal lee wave generation is not expected. Rather, strongly bottom-trapped motions and intense turbulent boundary layers are anticipated. Elevated turbulence is observed, but no stronger than that found above other rough topography;
- near-inertial fluctuations of a few 100-m vertical wavelengths, likely generated by the gale during the first week of the cruise;
- baroclinic semidiurnal fluctuations that picked up during the XCP/XCTD survey. These signals dominate the energy-flux of $O(1 \text{ kW m}^{-1})$ which is northward parallel to the slope rather than on- or offshelf (Fig. 1).

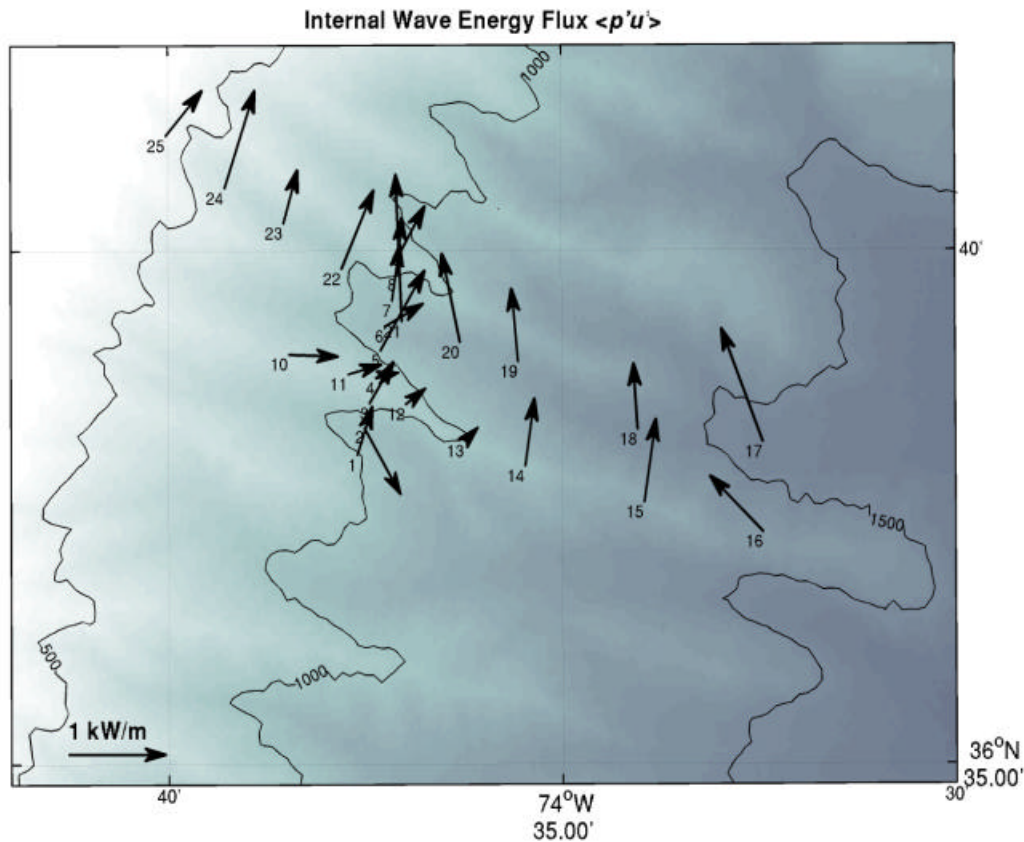


Figure 1: Depth-integrated station-average baroclinic energy-fluxes $\langle v'p' \rangle$ over the corrugated Virginia continental slope. Fluxes are northward parallel to the slope and $O(1 \text{ kW m}^{-1})$.

These dominant signals appear to have horizontal scales larger than the undulations of the slope bathymetry. Signals with scales comparable to the undulations are weak, are confined to the bottom few hundred meters, and will take additional effort to isolate. Preliminary results will be presented at the 2000 AGU Fall Meeting.

IMPACT/APPLICATION

The above program is part of ongoing investigation into topographically-enhanced fine- and microstructure in the wake of ONR's Topographic Interactions ARI over Fieberling Seamount. Diurnally-forced turbulent mixing found atop seamounts, although 100-1000 times higher than that in the ocean interior (Kunze and Toole 1997; Toole et al. 1997; Lueck and Mudge 1997), is insufficient to dominate basin-wide mixing and close the proposed thermohaline circulation. This has motivated examining other kinds of topography and other mechanisms, in particular, tidal forcing. Polzin et al. (1997) reported widespread elevated turbulence on the western flank of the Mid-Atlantic Ridge that they proposed is driven by tides.

TRANSITIONS

The energy-flux estimation technique is being used on other projects by the PI to examine internal tide energy budgets in Monterey Submarine Canyon and across Mendocino Escarpment. It has also proved a useful diagnostic for numerical modellers (Lu et al. 2000; Merrifield et al. 2000; Cummins personal communication 2000).

RELATED PROJECTS

The Virginia continental slope data will be compared with a similar data set collected on the continental slope outside of Monterey Bay. Energy-fluxes in the Monterey Slope data also are parallel to rather than across the slope. Larger fluxes are found radiating away from Mendocino Escarpment and into the mouth of Monterey Submarine Canyon. Turbulence levels along the bottom boundary of the Virginia continental slope are comparable to those observed over seamounts, escarpments and ridges. A multi-investigator NSF program has been launched to examine tidal mixing along the Hawaiian Ridge, which represents a much larger obstacle to the surface tides than topographic features that have been examined to date. While too early to be certain, existing evidence suggests that, except in abyssal waters below 4000-m depth, topographically enhanced mixing is not large enough to close the global conveyor belt as envisioned in Munk and Wunsch (1998). This would leave surface mixing as the only viable candidate for waters of 1-3 km depth in the temperate and tropical oceans (Rintoul and Sloyan 1999).

REFERENCES

- E. Kunze and J. M. Toole, 1997: Tidally-driven vorticity, diurnal shear and turbulence atop Fieberling Seamount. *J. Phys. Oceanogr.*, **27**, 2663-2693.
- J. R. Ledwell, A. J. Watson and C. S. Law, 1998: Mixing of a tracer in the pycnocline. *J. Geophys. Res.*, **103**, 21,499-21,529.
- Y. Lu, D. G. Wright and D. Brickman, 2000: Internal tide generation over topography: Experiments with a free-surface z-level ocean model. *J. Atmos. Oceanic Tech.*, submitted.
- R. G. Lueck and T. D. Mudge, 1997: Topographically-induced mixing around a shallow seamount. *Science*, **276**, 1831-1833.
- M. A. Merrifield, P. E. Holloway and T. M. Shaun Johnston, 2000: The generation of internal tides at the Hawaiian Ridge. *Geophys. Res. Letters*, submitted.
- J. E. Muench and E. Kunze, 2000: Internal wave interactions with equatorial jets. Part II: Acceleration of the jets. *J. Phys. Oceanogr.*, **30**, 2099-2110.
- W. Munk and C. Wunsch, 1998: Abyssal recipes II: Energetics of tidal and wind mixing. *Deep-Sea Res.*, **45**, 1977-2010.
- K. L. Polzin, J. M. Toole, J. R. Ledwell and R. W. Schmitt, 1997: Spatial variability of turbulent mixing in the abyssal ocean. *Science*, **276**, 93-96.
- S. R. Rintoul and B.M. Sloyan, 1999: Southern Ocean circulation, water-mass formation and interbasin exchange: Links to the large-scale overturning circulations. *EOS Transac.*, **80**(49), p256.

J. M. Toole, R. W. Schmitt, K. L. Polzin and E. Kunze, 1997: Near-boundary mixing above the flanks of a midlatitude seamount. *J. Geophys. Res.*, **102**, 947-959.

PUBLICATIONS

J. E. Muench and E. Kunze, 2000: Internal wave interactions with equatorial jets. Part II: Acceleration of the jets. *J. Phys. Oceanogr.*, **30**, 2099-2110.

E. Kunze, 2000: A review of salt-fingering theory. *Prog. Oceanogr.*, submitted.

K. L. Polzin, E. Kunze, J. M. Toole and R. W. Schmitt, 2000: The partition of finescale energy into internal waves and geostrophic motions. *J. Phys. Oceanogr.*, submitted.

E. Kunze, 2000: Waves: Vortical Mode. *Encyclopedia of Ocean Sciences*. J. Steele, S. Thorpe and K. Turekian, Eds., Academic Press, submitted.